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EFFECT OF COARSE AGGREGATE AND WATER/CEMENT RATIO ON INTRINSIC PERMEABILITY OF CONCRETE SUBJECT TO DRYING

F.D. Lydon
Cardiff School of Engineering, Division of Civil Engineering, University of Wales, Cardiff, Cardiff, CF2 1XH, UK.

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ABSTRACT

Intrinsic permeability of two types of concrete to nitrogen gas was tested; each had water/cement ratios of 0.40 and 0.50 and a volume fraction of coarse aggregate of 0.41 ± 0.01. Two coarse aggregates of 10mm single size were used, one a crushed limestone of low porosity, the other a sintered fly ash of high porosity. Test specimens (100mm diameter by 50mm thick) were water cured, then dried, during which weight loss and permeability were measured. All concretes had low permeability but consistently higher weight loss and permeability were found in the lightweight aggregate concrete specimens, indicating that accessible pores became available fairly quickly, despite the good quality of mortar used. Such behaviour may result from too rapid drying of the lightweight concrete test specimens. For a more realistic indication of permeability it is recommended that testing should be done in a laboratory environment that would, ideally, simulate insitu conditions. For similar 28 day strength both types of concrete had comparable permeability.

Introduction

The permeability of concrete to gas is related to its accessible pore structure and thus to its potential vulnerability to aggressive agents which can travel through it. Few, if any, mechanisms of attack depend only on one process but involve complex mass transport phenomena, hence the recommendation that concrete should be tested under realistic conditions (1). Tests of permeability to gas should not be expected to give unequivocal indications of durability, but they should provide information on accessible porosity and on the changes which can occur, which should lead to a better understanding of degradation processes.

Although natural aggregates can be quite permeable (2), it is generally assumed that undamaged, good quality, paste is of primary importance for low permeability, not least because it encloses the aggregate particles and reduces differences between them. But it is concrete, not paste, that is important and in the former there are likely to be pathways - such as at aggregate/paste interfaces (3,4) - not present in the latter.

Most data on permeability are reported at the end of a particular conditioning regime, typically when test specimens have been cured in some 'standard' way, followed by some drying to, perhaps, quasi equilibrium. When lightweight coarse aggregates are used (with considerable volumes of accessible porosity) (5,6) it could be supposed that (a) embeddment in good quality mortar renders their porosity irrelevant to permeating gas or (b) that if such porosity is relevant its effect on permeability would become apparent only after sufficient pore water had been removed from both mortar and aggregates to provide pathways for the gas. To check these, the change in permeability with drying should be observed. Thus water/cement ratio, curing regime and type of coarse aggregate are all influential factors.

The purpose of this work was to assess the role of these variables on the permeability to gas of two, good quality, structural concretes, each with similar volume fractions of coarse aggregate, one normal and one lightweight, in mortars of similar composition. By curing each in water at 20°C until seven days old, thus ensuring a sufficient degree of hydration to restrict access to the lightweight aggregate pore system, and then exposing them to air-drying, changes in permeabilities could be compared. Suppositions (a) and (b) should then be able to be checked. More prolonged water curing should reduce, further, access to the pores but even more lengthy periods of air-drying would be required for testing; oven-drying would greatly shorten the drying period but the temperature effects might be damaging and variable. However, increased access to aggregate pores might become very evident and sufficiently good correlation might be found between permeabilities after different curing regimes for useful comparisons between concretes. Hence different lengths of water curing followed by different drying histories could have fruitful results.

TABLE 1
Some Properties of Coarse Aggregates and Mix Proportions

Coarse aggregate	Mix proportions (1) (by mass)	Cement content (kg/m^3)	V_A (2)	28 day f_c (N/mm^2)
10mm crushed limestone	1 : 2.33 : 3.50 : 0.50	330	0.42	50.0, 50.0
R.D. (dry)(3) = 2.74 30 min. absorption (% dry mass) = 0.35	1 : 1.62 : 2.43 : 0.40	450	0.40	65.5, 65.5
10mm sintered fly ash R.D. (dry) = 1.57	1 : 2.40 : 1.92 : 0.50	330	0.42	42.0, 40.5
30 min. absorption (% dry mass) = 10.8	1 : 1.62 : 1.40 : 0.40	450	0.41	50.0, 48.0

(1) Portland cement : sand : coarse aggregate : free water.
(2) Volume of coarse aggregate/unit volume of concrete.
(3) Relative density, oven dry.

Test programme

To simplify matters, no admixtures were used in these mixes. One cement, a class 42.5 N Portland cement (7) and one sand, marine dredged, of medium grading (8) was used, with two types of coarse aggregate, details of which are given in Table 1. Two sets of mixes, of similar proportions to those chosen previously (9), were used to yield cement contents of about 330 and 450 kg/m^3. They had nominally free water/cement ratios of 0.50 and 0.40, to correspond to potentially good and excellent quality; with nominally free water contents of 165 and 180 kg/m^3 and the mix proportions shown in Table 1 they were of medium workability and of satisfactory stability. Mixes had similar volume fractions of coarse aggregates, not untypical of structural concretes. To ensure that the nominal free water/cement ratios were achieved, long-established practice was carefully followed in mixing. To the batched dry coarse aggregate was added the amount of water needed to satisfy the short-term absorption; this was mixed, left for a short while, covered, to achieve the nominal 'surface dry' state and then cement, sand and the required free water were added and mixed. Each mix was replicated within a few days and, from each, two standard 100mm cubes were tested as controls at 28 days. Concrete discs, 100mm diameter and 50mm thick were tested in pairs for intrinsic permeability to nitrogen gas, using a technique reported previously (9). Gas pressure was applied to one circular face of a disc and the volume flow rate measured at the other face, the gas flowing through the 50mm path. Intrinsic permeability was calculated from

$$D_s = \frac{2VL\eta p_1 10^{-5}}{A\left(p_2^2 - p_1^2\right)}$$

where D_s is permeability (m^2), V is volume flow rate (m^3/s), η is the viscosity of the gas (taken as 1.76×10^{-5} Ns/m^2), A is the cross sectional area of the disc (7.85×10^{-3} m^2), L the path length (50×10^{-3} m) and p_2, p_1 are the absolute pressures of the gas (bar), at the upstream and downstream faces, equal to 2 and 1 bars respectively. Testing was done at 20°C.

Three curing regimes were used. After storage in their moulds, covered, for 24 hours, discs were water cured (a) until 7 days old, then air dried in the laboratory for 60 to 76 days, then dried at 105°C for 3 to 6 days, or (b) until 56 days old then dried at 105°C for 4 to 6 days, or (c) as (b) but dried at 50°C for 21 to 45 days.

Checks on production control

From the mix proportions the theoretical densities of the freshly compacted concretes were calculated, assuming 98 percent compaction (based on previous experience) and the derived cement contents for the normal weight concretes were 330 and 443 kg/m^3 and for the lightweight concretes 333 and 441 kg/m^3. Based on the means of the replicated sets of the demoulded disc weights (i.e. 12 discs per mix) and the mean volume of disc, the mean density of each mix was calculated and the cement content again derived; the values were 333, 455, 328 and 444 kg/m^3 respectively, corresponding to the above values. Mean cube strengths of replicate mixes were nominally identical (Table 1), as were mean (of six) demoulded disc weights, which had coefficients of variation of 0.2 to 0.6% for normal weight concrete (NWC) and 0.4 to 0.7% for lightweight concrete (LWC). Calculated mean total water contents per disc, after immersion until 7 and 56 days old, and mean air dry disc weights at equilibrium were all close for companion mixes. It was therefore concluded that very good control was achieved in the production of the concrete mixes.

Permeability tests

Results from permeability tests are known to be very variable, because of the nature of the property being measured. From the results of the pairs of discs, for each test, made, cured and tested by one operator, an indication of the inherent variability of the procedure was calculated from

$$\bar{S} = \left[\left(S_1^2 + S_2^2 + \dots\dots + S_m^2\right) / m\right]^{1/2}$$

where S_1^2, S_2^2 ..... S_m^2 are the variances of sets 1, 2 ...... m and m is the number of sets. $\bar{S}$ is the mean standard deviation. (Although there is some indication that the standard deviation increases as the mean permeability increases, the scatter is very high; accordingly it is assumed that the former is approximately constant, for a given level of variability.)

Table 2 shows values of $\bar{S}$ for NWC and LWC for four curing conditions. Even though $\bar{S}$ for the lower water/cement ratio LWC was similar to that of the NWC mixes it was felt appropriate that both NWC mixes and both LWC mixes should be grouped together for comparison. Overall the values of $\bar{S}$ compare favourably with data from other investigations (10,11) and to that extent the test procedure can be seen to be reliable. Evidently, care is needed before concluding that apparent differences between concretes are real. Whereas the results from the LWC seem to be more variable (thus pointing the need for more specimens per test), if log D_s rather than D_s is used the resulting $\bar{S}$ values, also given in Table 2, do not indicate any signficant differences between the concretes. But it should be noted that the largest range of D_s values within any one curing regime is small, being a maximum of about 40:1.

TABLE 2
Mean Standard Deviations $\bar{S}$ of D_s(m^2 x 10^{-18}) and log D_s from Pairs of Discs

Concrete	Curing regime			
	Air dry(1)	Oven dry 105°C (a)	Oven dry 105°C (b)	Oven dry (2) 50°C
NWC D_s	1.98 n = 35(3)	15.32 n = 12	4.89 n = 12	2.85 n = 15
log D_s	2.208	1.381	1.02	1.206
LWC D_s	6.82 n = 32	38.16 n = 12	16.71 n = 12	4.86 n = 16
log D_s	2.203	0.913	1.434	0.765

(1) Air-drying on removal from water at 7 days old.
(a) Oven-drying after (1).
(b) Oven-drying on removal from water at 56 days old.
(2) Oven-drying on removal from water at 56 days old.
(3) n = number of pairs of discs.

Results

Figure 1 shows, for each mix, mean weight loss of pairs of discs with age and Figure 2 shows the change in permeability with age. After 68 ± 8 days in the laboratory, equilibrium was very closely approached, the rates of water loss being generally < 0.1g/day (< about 0.02 percent volume/day). The relation between permeability and weight loss is given in Figure 3 and values of the former at equilibrium are given in Table 3.

Discussion

On the basis of the cube strength results the NWC with water/cement ratio of 0.50 might be

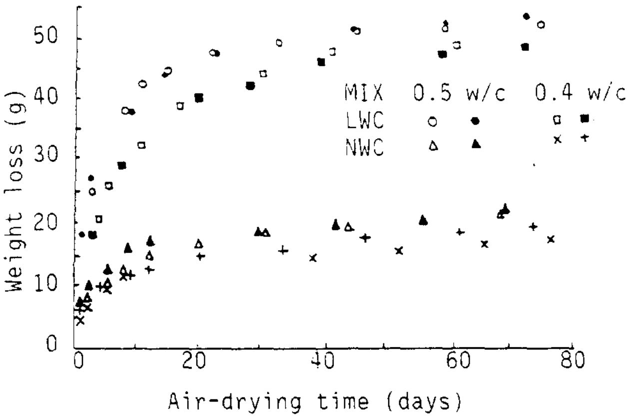

FIG. 1
Weight loss of discs with time

legitimately compared with the LWC of water/cement ratio 0.40. But strictly from the mix compositional aspect mixes of equal free water/cement ratios should be compared. From Table 3 it is seen that for the four conditioning procedures the permeability ranking order of mixes is always the same i.e. $\overline{D}_{s,NWC0.4} < \overline{D}_{s,NWC0.5} < \overline{D}_{s,LWC0.4} < \overline{D}_{s,LWC0.5}$, where $\overline{D}_s$ is the mean permeability and the suffixes $_{NWC0.4}$, $_{NWC0.5}$ ...... refer to NWC and LWC with water/cement ratios of 0.40 and 0.50 respectively. Generally the trends between the type of conditioning and $\overline{D}_s$ values are similar for the different concretes except for the LWC 0.50 water/cement ratio mixes where the permeability after 7 days' water curing and air-drying is higher than that after 56 days' water curing and 50^{o}C drying. Since this is the case for both (replicate) mixes it is likely to be a real difference and may be a reflexion of a change in the structure of that concrete due to the air-drying process.

The weight loss/time results in Figure 1 are qualitatively similar for both LWC and NWC but losses for the former are bigger because there are higher water contents to begin with leading to greater moisture gradients. Calculating 'water remaining' (W_r) values for the discs from the initial total water content (W_t) and the (W_ℓ) weight loss (i.e. $W_r = W_t - W_\ell$) gives results shown in Figure 4. The plots for both NWC sets of discs are qualitatively similar, with greater W_r values for the w/c 0.40, presumably because more water is bound into hydration products there. However the behaviour

TABLE 3
Ds(m^2 x 10^{-18}) Values after Different Curing Regimes (Curing Regimes as in Table 2)

Concrete	Air dry	Oven dry 105^{o}C (a)	Oven dry 105^{o}C (b)	Oven dry 50^{o}C
NWC/0.5	19.5	170.0	62.1	35.6
NWC/0.5	15.8	130.5	52.6	28.5
NWC/0.4	9.4	65.6	38.7	23.9
NWC/0.4	9.7	74.7	35.2	20.3
LWC/0.5	138.3	572.8	152.0	105.9
LWC/0.5	110.7	460.7	128.9	85.4
LWC/0.4	28.6	298.8	82.2	69.6
LWC/0.4	27.1	292.6	85.4	67.6

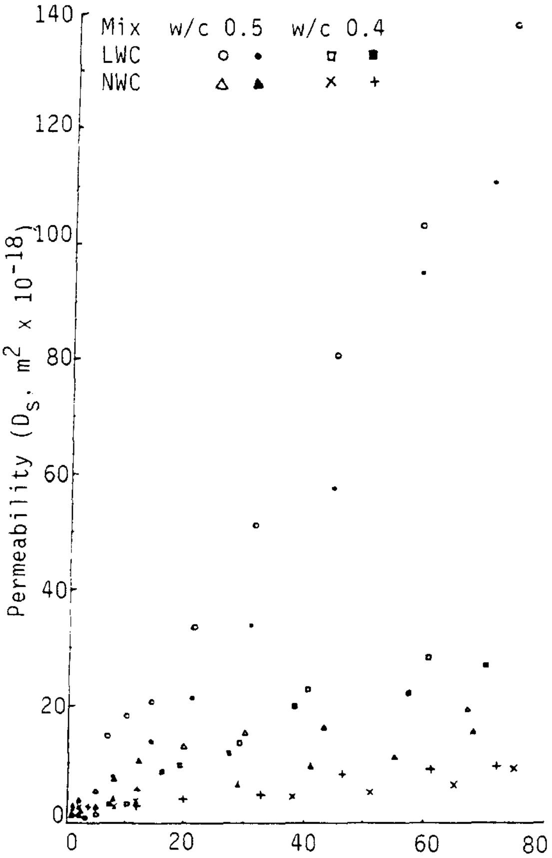

FIG. 2
Increase in permeability with time

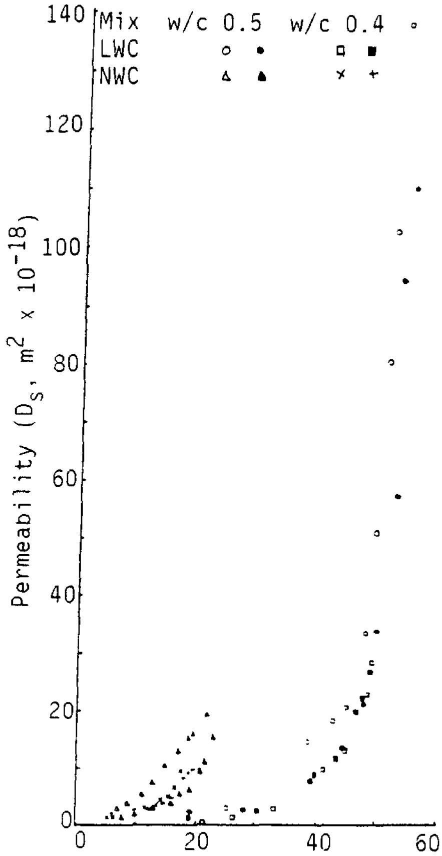

FIG. 3
Increase in permeability with weight loss

of both sets of LWC discs is very different, with rapid reduction in W_r initially, tending towards values similar to that of the 0.50 w/c NWC i.e about 60 ± 2g, which is about 10g less than the other NWC. While it is not possible, here, to elucidate the physical significance of these differences, because nothing is known about the division of 'water remaining' into free and bound water nevertheless the comparison between the two concretes with, for example, 0.40 w/c is surprising; it might be expected that the greater water content of the LWC (due to the LWA particles) would lead to more prolonged hydration and thus more bound water, but that does not seem to be the case. This may be due to the use of small specimens, which allows rapid drying and inhibits further hydration.

The results plotted in Figure 2 show that after only about 10 days' air-drying differences in D_s of the concretes are becoming evident and by 30 days there is significantly higher D_s in the 0.50 w/c LWC with the 0.40 w/c LWC beginning to show higher D_s values also. From Figure 3 qualitatively similar D_s/weight loss behaviour is evident for all concretes and there are distinctly different sets for NWC and LWC, the latter showing about 20g greater loss for a given permeability. Replotting the data semi-logarithmically (Figure 5) gives the following correlations:

NWC $W = 18.70 \log D_s + 1.30$ (n = 47 r = 0.96)

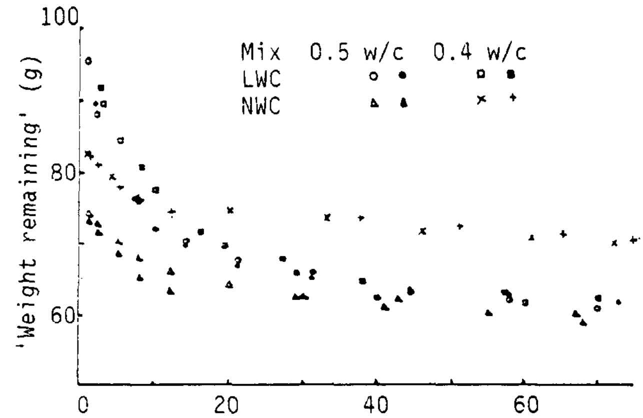

FIG. 4
'Weight remaining' with time

LWC $W = 18.89 \log D_s + 20.02$ (n = 41 r = 0.96)

where W is the loss in weight (g) from the end of the water curing to the time of testing and $D_s = m^2 \times 10^{-18}$.

This gives a difference in weight loss, over the range of permeability, of almost 19g and indicates that both correlations are almost parallel. For a very different concrete (with 'free' water/cement ratio of 0.71 and cement content of 265 kg/m^3 (12) a similar type of correlation can be found between weight loss (g) and air permeability ($m^2 \times 10^{-17}$) but with a more sensitive dependence of D_s upon W, for cubes cured in water for 7 and 28 days. (Similar forms were found for curing periods of 1,2 and 3 days but with much higher D_s values.)

Linear correlations are also found between calculated moisture content and D_s the former being relative to the weight after drying at 105°C . It appears that for a given moisture content there

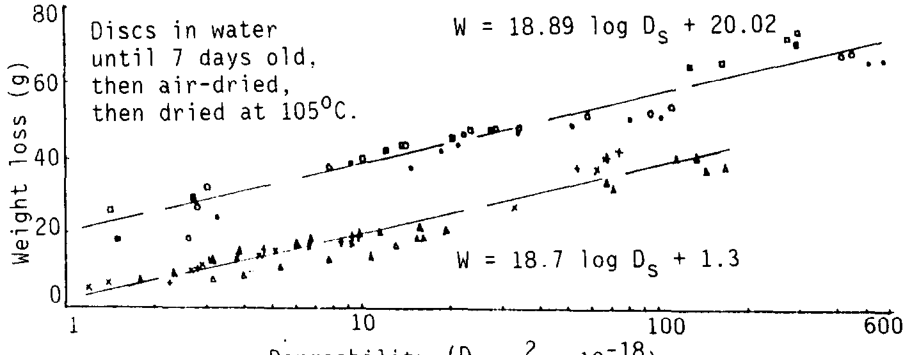

FIG. 5
Correlation of weight loss with log permeability

is consistently a higher permeability in the LWC. However, the ambiguity in the moisture content values, depending on how they are defined, makes it difficult to interpret such correlations. For example, for 'weight remaining' values of 60g and 95g the corresponding moisture contents are 14.6 and 23.2 percent by volume, compared to calculated moisture contents, as defined above, of 6 to 13 percent. Clearly the role of hydration is evident here again. Although weight loss is directly measured and explicit it depends, naturally, on mix composition, test specimen geometry and size as well as environment.

It is to be expected that, with LWC as used in this investigation, with a significantly accessible pore structure (5), an easy path could be provided for the gas were a low quality mortar to be used or stringent drying conditions imposed at an early age. But with a w/c of 0.50 (and 7 days curing) the LWC discs become increasingly more permeable with water loss after only 5 days; that is despite the proposition that after 4 to 5 days' water curing a discontinuous capillary pore system is formed in the paste sufficient to result in water permeability of 25×10^{-15} m/s (13) which is equivalent to about 25×10^{-22} m^2 and about 10^{-19} m^2 gas permeability (14). The measured permeability during the first days ranged from about 0.5 to 5×10^{-18} m^2 and after 8 days about 7.5 to 16×10^{-18} m^2 ; thereafter it increased monotonically with age, as drying proceeded, whereas with the corresponding NWC the rate was much less. Even with w/c 0.40 the LWC discs have, by 40 days, greater permeability than the NWC with the higher w/c ratio. By making simple assumptions, regarding water absorbed by the aggregate particles and subsequent water loss on drying, the estimated degree of saturation of aggregate pores, in the w/c 0.50 LWC discs, is about 22 % after 5 days, which decreases thereafter thus potentially allowing access to the gas if the mortar is permeable enough. With this w/c, for some reason, in the LWC it seems to be so. Permeability through the w/c 0.40 LWC is much less but is still greater than that through the corresponding NWC and indeed, after 40 days, than through the w/c 0.50 NWC. It is not clear why this should be so, but it may be that the LWC pores become available to the gas sooner than expected, because of the small size of disc.

Drying at 105°C (see Table 3) increased D_s by almost 10 times for the NWCs and for the better LWC and by about 4 times for the other LWC. There was no visible cracking in the discs and the implication seems to be that less evaporable water remained in the higher w/c LWC. Increasing water curing to 56 days followed by (i) 105°C drying or (ii) 50°C drying can also be seen to result in significant reduction in D_s values.

Estimated moisture contents (% volume) after 50°C drying are 0.6 and 1.0 for the NWC and 0.4 and 0.8 for the LWC (w/c 0.40 and 0.50 respectively), which will have some effect on the permeability values (15) but the data do not justify taking further account of that.

It is worth noting that despite the significant differences between these concretes they are all very good quality materials and even the most permeable is of acceptable standard, particularly when not subject to oven-drying.

Excellent correlation is evident from D_s results of the various curing regimes except for those involving LWC subject to air drying.

Previous work (11), on two concretes nominally the same as the NWC and LWC w/c 0.50 reported herein, found the D_s values indicated below, for discs previously water cured for two years:

Mix	10-12 weeks at 20°C and 68% RH	Oven-drying at 50°C	Oven-drying at 105°C
NWC/0.50	1×10^{-18} m^2	2×10^{-18} m^2	9×10^{-18} m^2
LWC/0.50	3×10^{-18} m^2	8×10^{-18} m^2	34×10^{-18} m^2

These values are relatively low, understandably; they are higher for the LWC and the differences between LWC and NWC increase with the severity of drying. They confirm that provided the mortar structure is of sufficiently low permeability (in this case by prolonged water curing) concrete permeability will still be low even after oven-drying but that the LWC will be the more permeable, presumably because of the accessible aggregate pore structure.

Conclusions

Differences were consistently found between the NWC and LWC used in this investigation which appeared to be associated with the accessible porosity of the LWA particles. This led to faster drying rates and higher permeabilities in the LWC despite having mortar of the same composition as that in the corresponding NWC. It is concluded that, for the materials, the test specimens and curing regimes used, even though all concretes were of good quality and low permeability, higher permeability to gas was evident in the LWC and was probably a result of the porosity of the LWA particles. This confirms a conclusion from previous work using a very different test technique (16).

It is recommended, especially if using small test specimens to assess LWC, that laboratory testing of permeability is carried out on specimens that represent, as realistically as possible the likely moisture state of the concrete insitu.

On the basis of equal 28 day standard cube strength LWC was of comparable permeability to NWC.

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